METHOD AND APPARATUS FOR COMBINING LASER LIGHT

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is related to and claims the benefit of co-pending United States Provisional Patent Application Serial Number 60/441,026, filed on January 17, 2003 and titled "Method and Apparatus for Combining Laser Light." The disclosure of U.S. Provisional Patent Application No. 60/441,026 is incorporated herein by reference in its entirety.

The subject matter of the present application may also be related to co-pending United States Provisional Patent Application Serial Number 60/441,027, filed on January 17, 2003 and titled "Method and Apparatus for Coherently Combining Multiple Laser Oscillators." The disclosure of U.S. Provisional Patent Application No. 60/441,027 is incorporated herein by reference in its entirety.

The subject matter of the present application may also be related to co-pending United States Patent Application Serial Number ______________ (Attorney Docket Number B-4757NP 621648-9) filed of even date herewith. The disclosure of this U.S. patent application (Attorney Docket Number B-4757NP 621648-9) is incorporated herein by reference in its entirety.

BACKGROUND

1. Field

This disclosure relates generally to coupling laser light in fibers and, more particularly, a method and apparatus for combining laser light in a fiber bundle.

2. Description of Related Art

In the fields of optical communication and lasers, particularly high power lasers, it is desirable to provide apparatus and methods for combining multiple optical sources into a single optical output and/or to provide multiple optical outputs from a single optical source. In this specification, the term "optical" is given the meaning used by those skilled in the art, that is, "optical" generally refers to that part of the electromagnetic spectrum which is generally known as the visible region together with those parts of the infrared and ultraviolet regions at each end of the visible region which are capable of being transmitted by dielectric optical waveguides such as optical fibers.

Combining multiple optical sources into a single optical output having optical power nearly equal to the sum of the powers of the individual sources can be accomplished through the combination of the optical sources. One apparatus known in the art for combining N sources is a 1xN fiber coupler. U.S. Patent No. 5,175,779, issued December 29, 1992 to Mortimore, describes a 1xN single-mode star coupler configured to couple light into multiple fibers at two wavelengths. In Mortimore, multiple single mode fibers are stripped of their primary coating and constrained around a single central fiber, which is also a single mode fiber stripped of its primary coating. All fibers are inserted into a tight fitting silica base glass capillary tube. The fiber and the tube are heated and pulled to form a tapered coupler. During the pulling process, light transmitted through the central fiber and at least one of the multiple fibers disposed around the central fiber is measured. When the light in the central fiber and the fiber disposed around the central fiber is nearly equal at the two desired wavelengths, the pulling process is terminated.

The 1xN star coupler disclosed by Mortimore and other similar apparatus known in the art provide the capability to combine optical sources at relatively lower powers. Furthermore, as the optical power in each fiber is increased, this prior art has the disadvantage that the combined power must propagate in the core of the single central fiber. When the combined optical power is high, undesirable nonlinear effects in, or damage to, the

single central fiber may occur. For example, at high optical powers, Stimulated Brillouin Scattering (SBS) may arise. This nonlinear optical effect results from the interaction of the light in the central fiber with acoustic waves in the fiber medium through which the light is propagating, producing inelastic backscattering of the light with a frequency shift equal to the frequency of the acoustic waves. The backward propagating light is amplified at the expense of the forward propagating light. Further, the acoustic waves may also be amplified by this effect, generating an acoustic intensity that can easily damage the single central fiber.

Splitting a single optical source into multiple optical outputs may also be provided by the 1xN star coupler described above, but the power handling capabilities of the coupler are again limited by the single central fiber. Further, if the optical source is a single plane wave, additional optical devices are needed to couple the plane wave into the single central fiber.

Devices are known in the art which allow an optical plane wave to be coupled to multiple fibers without using a single central fiber. For example, U.S. Patent No. 5,852,699, issued December 22, 1998 to Lissotschenko et al., discloses a coupling element having an array of lenses where each lens focuses an incident light beam onto a specific fiber in a fiber bundle. Hence, the coupling element splits the incident plane wave into multiple light beams, each of which are directed to a separate optical fiber.

The coupling efficiency for coupling an optical plane wave into multiple fibers using the approach disclosed by Lissotschenko (or other similar techniques known in the art) is generally limited to about 30%. Even assuming perfect alignment, the coupling efficiency is limited by the packing of both the fibers in the fiber bundle and the lenses in the array of lenses. The coupling efficiency is further limited by clipping that occurs at the edge of each lens in the array. Finally, the coupling efficiency is reduced because the fiber modes only accept a Gaussian-profiled fraction of the input beam. Therefore, even though the optical plane wave may be a high power optical beam, a significant portion of that power is lost when coupling the beam into multiple fibers using apparatus and methods known in the art.

Therefore, there is a need in the art for a method and apparatus for combining the optical power of multiple optical fibers to provide a single high power optical output. There is also a need in the art for a method and apparatus for coupling an optical beam into multiple optical fibers at a greater coupling efficiency than other methods and apparatus known in the art. Further, there is a need in the art for efficiently coupling an optical beam in free space into multiple optical fibers, and coupling optical beams propagating in multiple optical fibers into free space.

SUMMARY

Embodiments of the present invention provide a method and apparatus for providing for the coherent combination of the optical power in multiple optical fibers into a single optical output and provide for the coupling of the light of an optical source into multiple optical fibers. Embodiments of the present invention may be fabricated using materials and techniques well known in the art.

Embodiments of the present invention provide a controlled amount of interconnectivity between a controlled number of neighboring optical fibers, while also providing a relatively collimated beam from the fiber ensemble. The fibers may all have the same core size and/or refractive index or the core sizes and/or refractive indices of the fibers in the fiber ensemble may vary. In preferred embodiments of the present invention, the fibers in the fiber ensemble are bundled together, fused and stretched. The stretching decreases the core size of the fibers, which increases the size of the optical mode guided by the core. The stretching simultaneously decreases the spacing between the cores.

By controllably decreasing the core size and spacing, the optical power originally guided exclusively by any one of the cores may be controllably coupled to the neighboring cores. As discussed above, power coupling between adjacent optical fibers by stretching the fibers is known in the art. However, unlike the known prior art, the fused bundle in embodiments of the present invention is cut and polished (or cleaved) at a selected position

along the necked-down bundle, where the fibers are stretched and fused. The point at which the fused bundle is cut and polished (or cleaved) provides a facet to which an optical beam may be coupled or from which an optical beam can be output.

When the multiple fibers are connected to multiple optical sources, an optical beam will emerge from the facet. The optical beam will consists of beamlets, each larger (10's of microns) than the normal size (~ 6 microns diameter) of fiber-optic beams, and thus not as prone to damage the output facet.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings.

FIG. 1 shows an embodiment of the present invention comprising a bundle of optical fibers fused at one end.

FIG. 1A shows an enlarged view of the fused end of the fiber bundle depicted in Figure 1.

FIG. 2A shows a first step in fabricating an embodiment of the present invention where a plurality of fibers is disposed adjacent each other.

FIG. 2B shows a subsequent step in fabricating an embodiment of the present invention where the plurality of fibers are fused and stretched so as to taper the fibers.

FIG. 2C shows the final configuration of an embodiment of the present invention where the stretching of the plurality of fibers is completed and the fused bundle is cleaved.

FIG. 3A illustrates a cross section of the plurality of fibers assembled in an array prior to stretching.

FIG. 3B illustrates a cross section of the plurality of fibers after the fibers have been stretched and the individual diameters reduced.

FIG. 4A presents a linear plot of calculated mode shapes for fibers that have decreased diameters due to stretching.

FIG. 4B presents a semi-logarithmic plot of the calculated mode shapes shown in FIG. 4A.

FIG. 5A illustrates an enlarged view of the fused end of the fiber bundle depicted in Figure 1A according to one embodiment.

FIG. 5B illustrates the bundle of optical fibers according to the embodiment shown in Figure 5A.

FIG. 6A illustrates the bundle of optical fibers according to another embodiment.

FIG. 6B illustrates an enlarged view of the fused end of the fiber bundle depicted in Figure 6A.

DETAILED DESCRIPTION

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Further, the dimensions of certain elements shown in the accompanying drawings may be exaggerated to more clearly show details. The

present invention should not be construed as being limited to the dimensional relations shown in the drawings, nor should the individual elements shown in the drawings be construed to be limited to the dimensions shown.

Figure 1 illustrates the preferred embodiment of the invention, which comprises a large bundle of regularly arrayed optical fibers 100. The optical fibers 100 are preferably single-mode fibers. The optical fibers 100 are fused at one end and stretched. The fused end is cut and polished (or cleaved) to produce a facet 110 through which a free space optical beam can be received or transmitted. Figure 1A shows an enlarged view of the fused fibers 100 and the facet 110. Figure 1A also shows a minimal taper 120 of the bundle at the point where it is cut and polished to produce the facet 110. However, the preferred embodiment will in general have more taper.

The preferred embodiment of the present invention is fabricated by assembling the optical fibers 100 in the fiber bundle in a regular array. Such arrays include hexagonal close packing, square packing, and a three-nearest-neighbor packing. Although manufacturing tolerances may result in a certain amount of randomness in the array, the device is still useful even if the optical fibers 100 are not perfectly arranged. This array of fibers is then fused together and stretched using techniques well known in the art, such as those techniques used for the fabrication of tapered fiber couplers. After the bundle of fibers has been fused and stretched, the bundle is cut and polished, or cleaved, at a selected location to provide the facet 110. The facet 110 provides for the entrance of a single beam into the apparatus and the distribution of that beam among the optical fibers in the array. The facet 110 also provides for the exit of a single beam from the apparatus, which may be fed by optical sources coupled to the multiple fibers 100.

Figures 2A – 2C illustrate a typical process for fabricating embodiments according to the present invention. Figure 2A shows the array of fibers 100 assembled within a tube 190. Figure 2B shows the array of fibers 100 after a fusing and stretching process is begun. As shown in Figure 2B, the stretching process causes the array of fibers 100, as well as the tube

190, to obtain a taper 120. Figure 2C shows the completion of the fabrication process, in which the array of fibers 100 terminates in a smaller diameter fused fiber section 111, which is cleaved to provide the facet 110. The location at which the fused fiber section 111 is cleaved is a matter of design, and as will be seen, can be used to determine the amount of coupling between neighboring fibers 100 in the array.

To make fabrication of the device simpler, to facilitate assembly and maintenance of specific array patterns throughout the fabrication procedure, or to improve the device's performance, several techniques used in the glass fabrication art may be used. For example, the bundle of fibers 100, in an array with the desired configuration, can be first assembled inside a tube 190 (as shown in Fig. 2A) possibly having a lower melting temperature than the softening temperature of the fused silica fibers 100. This assembly can then be heated to the temperature where the tube 190, but not the fibers 100, melts, and the melted tube 190 is allowed to flow into the spaces between the fibers 100. Fluorosilicate glass is one type of material that may be used for the protective tube 190. This assembly may then be subsequently further heated, to a temperature at which the fibers 100 soften, and the stretching and tapering is done. If the heating and stretching is uniformly carried out, the geometric pattern of the array will be more easily maintained with the use of this melted matrix than when air pockets occur between the fibers 100. To avoid the loss of the propagating light into this melted matrix, the tubing glass is preferably chosen to have a refractive index equal to that of the fiber cladding. However, tubing glass having a lower refractive index may also be used, and is generally easier to obtain. The melted matrix then functions as an outer cladding, guiding the light within the fiber claddings. Similar results could be achieved by first coating each individual fiber 100 (or the preform from which it is made, or as it is being pulled) with the lower melting temperature glass.

The degree to which the fused portion of the array is stretched is a matter of design. Typically, the fused portion of the array is stretched to give the desired mode size and degree of coupling between fibers. In general, when the array of fibers 100 is stretched, the cross-sectional shape of each fiber 100 can be preserved, except that the fiber 100 is

proportionately miniaturized. Shown in Fig. 3A is a cross section of an array of fibers 100 with cores 130 before stretching, and shown in Fig. 3B is the same array of fibers 100 with cores 130 after stretching. In general, the diameter of each fiber 100 is reduced to be on the order of tens of microns, while the stretched region may be stretched several centimeters or more. It has been found experimentally that >~2X stretching provides the desired results. Note that Fig. 3A appears to depict fibers 100 with approximately the same core size. Alternative embodiments of the present invention may comprise fibers 100 with different core sizes and/or refractive indices.

The procedure used to calculate the coupling of the fibers to their neighbors consists of selecting a packing arrangement, a ratio of core size to cladding size (that is, the particular type or specifications of the fiber), and a degree of stretch and length of the stretched region, that produces the desired coupling. What makes coupling to neighbors possible is the fact that the size of the mode propagating through the fiber increases as the V-number of the fiber gets smaller and a greater fraction of the power propagates outside the core, overlapping adjacent cores. The V-number is a well-known fiber parameter and is defined as:

$$V = \rho k\left(n_{core}^2 - n_{clad}^2\right)^{1/2}$$

where ρ is the radius of the core, k is the wavenumber of the light, n_{core} is the refractive index of the fiber core, and n_{clad} is the refractive index of the fiber cladding.

Mode shapes of light propagating within an optical fiber can be calculated and Figure 4A presents instructive examples of such calculations. Figure 4A presents plots of local intensity and the curves shown in the plots have been normalized so that the total power (the integral of the intensity over the fiber area) is the same in all cases. For example, if the original fiber diameter is 120 μm with a step-index core diameter of 6 μm, the intensity of the mode shape calculates to be the curve 311 in Figure 4A, with the profile inside the core being shown by curve 312 (roughly the portion of the curve 311 located between the points ± 3 μm distance from the core). As can be seen, the intensity of curve 311 quickly tapers off to essentially zero at locations roughly 10μm radially outwards from the core. The decrease in

the intensity is more clearly illustrated in FIG. 4B, which presents a semilogarithmic plot of the intensities shown in FIG. 4A. Because the core of the nearest fiber would be 120 μm away, there is effectively no coupling between the fibers 100 in the array in this configuration.

If this same fiber is now contemplated as being stretched so that its diameter is 60 micrometers (2X stretching) then the calculated mode shape is as shown by curve 321, with the profile inside the now-smaller core being shown by curve 322 (roughly the portion of the curve 321 located between the points ± 1.5 μm distance from the core). Figures 4A and 4B show that a greater proportion of the mode is now outside the core. In this configuration, the mode has a little intensity as far away as locations roughly 60 μm radially outwards from the core. Because the core of the nearest fiber would be 60 μm away, there is a small amount of desirable coupling between the fibers 100 in the array.

If the fiber is further stretched so that its diameter is only 42 μm (about 3X stretching), the mode shape calculates to be curve 331, with the profile inside the core being shown by curve 332 (roughly the portion of the curve 331 located between the points ± 0.75 μm distance from the core). Figures 4A and 4B show the mode shape in the stretched fiber to be quite widely spread. As can be seen in Figure 4B, the intensity of the mode is still quite significant at locations roughly 15 μm and more radially outward from the core.

Figure 4B also shows with curve 341 the calculated mode shape for 4X stretching, that is, where the fiber diameter is only about 30 μm. As can be seen in Figure 4B, the mode intensity is significantly less than that seen with lesser degrees of stretching. However, the intensity within the core (shown by curve 342 and roughly the portion of the curve 341 located between the points ± 0.50 μm distance from the core) is only slightly greater than the intensity outside of the core. Hence, with 4X stretching, there is likely to be significant coupling with other fibers 100 in the array.

Figures 4A and 4B illustrate how the intensity spreads as the fibers are stretched. Figures 4A and 4B also show that a degree of stretch can be found that gives a desired amount of coupling.

If the device is to be used to couple a free space beam into an ensemble of fibers 100 as shown in Figs. 5A and 5B, the sum of the mode shapes can be calculated, and the core/cladding size ratio and stretch selected, to maximize coupling of the free space beam into the core ensemble. In the limit of very large taper, the device can be heuristically thought of as simply a tapered fused silica rod, with the wide end separating into an ensemble of fibers. The single optical input enters at the facet 110. The fibers located nearer to the center of the array will generally receive the majority of the light, while the fibers located at the perimeter of the array will generally receive less light. So long as all the light in each fiber is derived from the same single optical input, the light in each optical fiber will be coherent. As it propagates, nearly all of the light will be collected by one or another of the weakly guiding cores arrayed inside the rod. As the rod enlarges into a bundle, the light collected by each core condenses to a smaller size, until at the other end of the device, the light has distributed itself into the ensemble of fibers to provide a plurality of distributed optical outputs.

Alternatively, the device may be used to combine multiple optical inputs into a single combined optical output as shown in Fig. 6A and 6B. All the optical inputs are preferably coherent and in phase, and may be derived from the same source. One technique for providing multiple coherent input beams and controlling them to have the same phase at the facet 110 is discussed in U.S. Patent 6,400,871. If the optical inputs are not coherent then undesirable effects such as speckling may be present in the combined single optical output. Also, the quality of the combined single optical output will be significantly reduced if the optical inputs are not derived from the same source and they have different wavelengths. Because of the effects shown in Figures 4A and 4B, as the core of each fiber becomes smaller, the diameter of the beam in the fiber becomes larger. As a result, each of the beamlets (one beamlet per fiber in the array) which comprise each optical input in each

optical fiber emerges from the facet 110 having a diameter (~10's of microns) larger than the normal diameter of each beamlet in each optical input (~6 microns). As a result, the combined single optical output can have a diameter in the 100's of micrometers or more, depending on the size of the bundle. Because of the large diameter of the individual optical outputs emerging from the facet 110 to form the combined single optical output, the facet 110 is less likely to incur damage, and nonlinear SBS (Stimulated Brillouin Scattering) effects can be reduced.

From the foregoing description, it will be apparent that the present invention has a number of advantages, some of which have been described herein, and others of which are inherent in the embodiments of the invention described or claimed herein. Also, it will be understood that modifications can be made to the apparatus and method described herein without departing from the teachings of subject matter described herein. As such, the invention is not to be limited to the described embodiments except as required by the appended claims.